A GIS toolkit for measuring and mapping space-time accessibility from a place-based perspective

This paper introduces a novel GIS toolkit for measuring and mapping the accessibility of individuals to services. The toolkit contributes to earlier implementations by combining aspects of both place-based and person-based accessibility measures. To this end, place-based accessibility measures are derived from a person-based framework by considering space-time prisms which are centred at service facilities rather than individual anchor points. The implementation is also innovative by explicitly accounting for the opening hours of service delivery in its accessibility measurement. In addition, the toolkit is aimed to be user-friendly and to generate insightful and comprehensible results for non-technically-oriented users, which is illustrated in a brief case study about library accessibility in Ghent (Belgium).

Keywords: accessibility; GIS toolkit; place-based approach, space-time prism

## 1. Introduction

Accessibility is a fundamental concept in transport geography and urban planning. It refers to individuals' ability to travel and participate in activities given the available transport and land use system (Pirie 1979, Pooler 1987). To assess accessibility, researchers have relied on various accessibility measures. Roughly, these can be divided into place-based and person-based measures (Miller 2007). *Place-based measures* associate a level of accessibility to a location or spatial unit of analysis (e.g. census tract, ward, traffic analysis zone, etc.). They express accessibility in terms of physical separation between desired activity locations and a

key location in an individual's daily life, such as the residence or workplace. The family of place-based measures includes such well-known and commonly applied accessibility measures as the travel time or distance to the nearest opportunity and the number of opportunities within a particular area or within a specific cut-off distance from a given location. While rigid, easily implementable and insightful, place-based measures have often been criticised as they tend to reduce individual travel behaviour to a (set of) key location(s), while ignoring important temporal constraints on activity behaviour such as the opening hours of urban opportunities and the limited availability of discretionary time on the part of an individual (Neutens *et al.* 2010b). This criticism has called a foundation for the development of person-based accessibility measures.

*Person-based measures* are specified at the lowest level amenable to the social sciences, i.e. the individual. Drawing on concepts of time geography (Hägerstrand 1970), these measures express accessibility on the basis of detailed observations of the spatiotemporal constraints individuals are faced with. Hence, person-based measures allow accessibility to fluctuate during the course of the day as well as across persons, as has been shown by, among others, Kwan (1998, 1999), Kim and Kwan (2003), Miller (2007), Casas (2007), Schwanen en de Jong (2008), Yu and Shaw (2008), Neutens *et al.* (2010b, 2010c), and Páez *et al.* (2010). Whilst more subtle and detailed, they are also more complex to calculate than place-based measures – although this difficulty has been increasingly overcome by the growing capabilities of geographical information systems (GIS) in recent years. In addition, the assessment of person-based accessibility requires dedicated and representative information about the activities (e.g. travel diaries) of sampled individuals, which is in many cases unavailable or at least difficult to collect.

From a cartographical point of view, person-based measures have an important disadvantage over place-based measures, since they cannot be mapped in a straightforward

manner. This is because person-based measures associate accessibility values to individuals instead of locations. Three alternative approaches have been used to represent person-based accessibility on a map (Fig. 1). A first approach consists of delineating all locations that are accessible to an individual by mapping one's potential path area (PPA) or feasible opportunity set (FOS) in between two or more pairs of fixed activities (see e.g. Kwan 1999, p. 215, Kim and Kwan 2003, p. 85, Weber 2003, p. 57, and Miller and Bridwell 2009, p. 68) (Fig. 1a). Second, individual accessibility values may be mapped at locations where an individual spends much time during the day, such as the residence or work place. Examples of such maps are available in Weber and Kwan (2002, p. 232) and Weber (2003, p. 61) and Neutens *et al.* (2010c, p. 1051) (Fig. 1b). As argued by Weber and Kwan (2002), this representation may be misleading because the values assigned to static locations do not depend on these locations but rather on individuals who may travel widely throughout the study area. Third, person-based accessibility can be aggregated across individuals and mapped at the activity locations, for instance by using the concept of locational benefits (see e.g. Miller 1999, p. 827, Neutens *et al.* 2010a, p. 1206) (Fig. 1c).

A problem with the three person-based accessibility maps in Fig. 1 is that they fail to represent the fluctuation of individual accessibility values across every single location in the study area. This is in contrast with place-based accessibility, which can be easily summarized in a conventional area-covering map in which each location is allotted a unique accessibility value (e.g. see some recently published maps by El-Geneidy and Levinson (2007), Nettleton *et al.* (2007), Achuthan *et al.* (2010), Colclough and Owens (2010), Drew and Rowe (2010), and Lei and Church (2010)).

Fig. 1 – Three alternative approaches to map person-based accessibility: potential path area (PPA) or feasible opportunity set (FOS) between fixed activities (a), individual accessibility

geocoded to home location (b), aggregated individual accessibility geocoded to destination (c).

This paper attempts to make a link between place-based and person-based tools by introducing *PrismMapper*, a GIS toolkit for measuring and mapping accessibility to service facilities. To this end, we will consider place-based measures that implement person-based concepts building on time geography. In addition, the toolkit is intended to be simple, robust and comprehensible such that it is directly appealing to all kinds of end-users. The toolkit is available from http://geoweb.ugent.be/cartogis/research/prismmapper. The remainder of the paper is structured as follows. The next section discusses related tools to measure accessibility and provides a motivation for the current contribution. Section 3 presents the toolkit and the accessibility measures it implements. To illustrate its relevance for policy makers, a case study on the accessibility of public libraries in Ghent (Belgium) is elaborated in section 4, followed by conclusions in section 5.

## 2. Related tools

Many existing information systems and services implement accessibility measures in various ways. GPS devices and routing systems, for instance, are able to calculate travel times and distances, i.e. simple place-based accessibility measures. These implementations, however, are usually a black box to the user. Web services, such as the OpenRouteService (http://openrouteservice.org) (Neis *et al.* 2007), the National Accessibility Map of the Netherlands (http://www.bereikbaarheidskaart.nl), and the recently released Mapnificent (http://www.mapnificent.net), offer explicit tools to map accessibility measures. While useful, such services are often limited on two aspects: (i) meta-information on the data sources and exact methods they use to assess the implemented accessibility measures, and by consequence (ii) the freedom they offer the user to manipulate or configure these data and methods.

On the other hand, dedicated GIS packages or extensions, most of which implement place-based measures, can cope with the above shortcomings. Travel times and distances, are supported in many GIS packages either by the calculation of beeline distances in unconstrained space or shortest paths within a geographic network. A noteworthy toolkit going beyond these simple measures is Flowmap (http://flowmap.geog.uu.nl), developed at the University of Utrecht and released in 1990. Flowmap has been specifically designed to handle spatial flow patterns, but also supports computing travel costs along a network, and modelling the market areas of existing or planned facilities. In 1998, the Environment Systems Research Institute (ESRI®) introduced the Network Analyst extension of its ArcView™ software (nowadays ArcGIS™). The Network Analyst allows calculating and mapping shortest paths, nearest facilities, and service areas over a given network (N. N. 1998). O'Sullivan *et al.* (2000) have described a desktop GIS application to map isochrones for accessing facilities through public transport. In 2004, Liu and Zhu (2004) have presented their own ArcGIS$^{TM}$ accessibility extension. Although their implementation includes tools that are currently also covered by the Network Analyst extensions, such as origin-destination travel cost matrices, it additionally supports more complicated place-based measures such as gravity- and utility-based measures and catchment profiles. Despite the authors' argumentation that the extension is available to a wide range of users, any further reference on how to obtain and use their toolkit is regretfully missing. The same is true for the recent Urban.Access tool (Benenson *et al.* 2010) which allows for the mapping of place-based measures based on detailed car and bus travel times.

Regarding person-based accessibility, especially in the field of exploratory spatiotemporal data analysis and visualisation, several implementations exist which may assist the assessment of person-based accessibility measures without explicitly operationalizing these (e.g. Andrienko and Andrienko 1998, Kraak 2003, Yu 2006, Andrienko *et al.* 2009,

Andrienko *et al.* 2010). In addition, there have been early operationalizations of fundamental time-geographical concepts such as (Lenntorp 1976, Kitamura *et al.* 1981, Landau *et al.* 1982, Kondo and Kitamura 1987, Villoria 1989, Nishii and Kondo 1992). These have been characterised by an unrealistic modelling of the travel environment as they ignore the transportation network (Kwan and Hong 1998). This shortcoming has been addressed later in both theoretical (Neutens *et al.* 2007, Miller and Bridwell 2009, Kuijpers *et al.* 2010) and empirical work (Kwan and Hong 1998, Kwan 1998, Kim and Kwan 2003, Kwan and Weber 2003, Neutens *et al.* 2010b, Neutens *et al.* 2010c).

In 2000, Miller and Wu (Miller and Wu 2000) introduced the first true person-based toolbox which allows mapping three different benefit measures for an individual to participate at discretionary activities in space and time. This prototype is a user-friendly front-end / back-end application for measuring an individual's accessibility. Recently, Neutens *et al.* (2010d) presented a stand-alone person-based accessibility toolkit for assessing the opportunities for joint activity participation. Their toolkit provides a dynamic and animated view of the activity locations that are accessible to a person or group during the course of the day. Both toolkits are characterised by a sincere demand for detailed input data about the individual activity schedules. Not only is such information merely occasionally available for a sample of individuals, it is also questionable whether this sample data is representative in all its dimensions for the associated population. This delicate issue has never been profoundly addressed in studies on person-based accessibility, which questions the usefulness of the related tools. More than that, given that the necessary information would be available, these toolkits are unable to generate maps of the accessibility of an entire population – let alone area-covering maps (cf. Fig. 1) – thereby passing over the synoptic power of maps. This could be considered a significant inadequacy in the eyes of decision makers or urban planners dissuading them from using these tools. In addition, both toolkits implement comparable

benefit measures which are obtained from complex utility functions. The complexity of these functions obscures the interpretation for end-users who do not have prior knowledge about time geography and accessibility modelling. Finally, a last and perhaps most poignant point of critique is that the toolkits nullify the added value of person-based measures since they only account for the spatiotemporal constraints on the part of the individual while neglecting the time constraints on the part of the urban facilities (e.g. opening hours, waiting times).

The *PrismMapper* toolkit introduced in this paper aims to contribute to the set of existing implementations in at least three ways. First, it tends to support a comprehensible set of simple and rigid place-based accessibility measures. That is to say, the measures should be meaningful, interpretable and self-evident, even for end-users who are not acquainted with the accessibility literature. Second, while taking advantage of the mapping opportunities of place-based measures, it seeks to implement some temporal properties that are implied in person-based measures by considering reverse space-time prisms (see section 3.1). Third, *PrismMapper* accounts for the space-time constraints of service delivery by explicitly considering the opening hours of service facilities.


## 3. PrismMapper

This section will first describe the place-based accessibility measures implemented in *PrismMapper* and then give an overview of the system.

### 3.1. Accessibility measures

Most person-based measures rely on the well-known time geographical framework originated in the 70's by Hägerstrand (1970). The basic unit of analysis in time geography is the *space-time path*, i.e. an individual's daily trajectory in space and time. Space-time paths comply with three types of constraints: (i) an individual's physiological capabilities (capacity constraints), (ii) an individual's commitments that bind him/her to specific locations and time

budgets (coupling constraints), and (iii) rules stemming from norms and laws (authority constraints). These constraints delineate a set of space-time points accessible, i.e. physically reachable, by the individual. The subset of this set which corresponds to an individual's space-time budget that is available between an origin and a destination is referred to as a *space-time prism* (STP). The origin and destination are denoted as the anchor points of the STP. STPs are typically represented in a 3D space-time cube where a vertical time axis is integrated with a flattened topography (Fig. 2, Fig. 3a). The STP of an individual with a time budget from $t_i$ to $t_j$ between an origin $o$ and a destination $d$ can be formally described as:

$$STP(o, d, t_i, t_j) = \{(x,t) | t_i \leq t \leq t_j \wedge T(o,x) \leq (t - t_i) \wedge T(x,d) \leq (t_j - t)\} \qquad (1)$$

with $T(o,x)$ the travel time from $o$ to $x$, $T(x,d)$ the travel time from $x$ to $d$. In the case of an isotropic travel environment with a constant finite maximum velocity – as has been understood in Fig. 2 and Fig. 3 – a STP is obtained from the intersection of a cone oriented forward in time and a cone oriented backward in time (Miller 2005). These cones respectively represent the condition that all parts of the STP should be reachable from the origin within the time budget and that the destination should be reachable within the time budget from each point of the STP.

While the STP is a powerful concept to model a global level of an individual's physical accessibility, many studies have used it to assess, specifically, individual accessibility to services by simply considering a service accessible on the basis of the presence of its location within the space-time prism (e.g. Neutens *et al.* 2010d). Hence, they overlook the time constraints of services, which are however only delivered and thus accessible within well-defined opening hours. Therefore, in addition to STPs, *PrismMapper*

accounts for the opening hour regimes of facilities in order to decide on their accessibility (see equation (2) further on in this section).

Fig. 2 – Space-time prism and related concepts

The cartographical equivalent of a space-time prism, i.e. its spatial footprint, is called a *potential path area* (PPA) (Fig. 2). Since one individual may have more than two anchor points in the course of a day and thus multiple STPs, the mapping of PPAs across multiple individuals soon becomes cluttered (cf. Fig. 1a). To overcome this cartographical problem, *PrismMapper* considers 'reverse' STPs which are centred at service facilities instead of individual anchor points, and which we will refer to as *reverse space-time prisms* (RSTPs). The RSTP for a facility $f$ and its opening hour time slot from $t_p$ to $t_q$ with respect to a time budget from $t_i$ to $t_j$, a maximum travel time $c$, and a minimum activity duration $m$ is given by:

$$RSTP\left(f, t_p, t_q, t_i, t_j, c, m\right) =$$
$$\left\{ (x,t) \left| \begin{array}{c} t_i \leq t \leq t_j \wedge \\ \min\left(t_q, t_j - T(f,x)\right) - \max\left(t_p, t + T(x,f)\right) + \leq m \\ \max\left(t_p, t + T(x,f)\right) + m + T(f,x) \leq t_j \wedge \\ T(x,f) + T(f,x) \leq c \end{array} \right. \right\} \tag{2}$$

The RSTP comprises all space-time points from which an individual may travel to a facility in order to visit it for at least a given amount of time during its opening hour such that the individual may return back to his/her origin within the given time budget and maximum travel time. The difference between a STP and a RSTP is illustrated in several cross sections through space-time shown in Fig. 3. Instead of looking at the accessible locations in between two anchor points, the PPAs of RSTPs capture all anchor points that may be interpreted as

valid pairs of a coinciding origin and destination, such that an individual can travel from the origin to visit the facility and return to the destination within the time budget and travel time threshold at hand. The interpretation of such back-and-forth trips is straightforward, since they are common in daily life, especially with respect to residential locations, i.e. home-facility-home trips.

In contrast to conventional STPs, RSTPs are not obtained from the intersection of two cones, since they are determined by different conditions. Fig. 3a, b, and c show how different RSTPs evolve from different configurations of the individual time budget and the facility opening hour. The RSTPs have a cylindroconical shape which is determined by the ultimate anchor points from where the facility can be reached for a certain minimum duration during its opening time window and which can thereafter be returned to within the time budget and within the considered maximum travel time.

The boundary of an RSTP may have several bends at the space-time points where different constraints meet. A bend between the conical and the cylindrical part of an RSTP may occur at the cut-off distance corresponding to the maximum travel time $c$, as applies to Fig. 3b and Fig. 3d. In these cases, the distance corresponds to halve of $c$ because travel times are symmetrical in isotropic space. In Fig. 3c, a smaller cut-off threshold applies, given that there is less time to return within the time budget after a meaningful visit to the facility. Furthermore, it is noted that the RSTP in Fig. 3b has a second, inner bend in its conical shape, which occurs at the intersection of ultimate anchor points from where the facility can be reached at its closing time and those that can still be returned to from the facility at the end of the time budget.

Fig. 3 – Cross section through space-time of a STP (a) and three RSTPs according to different configurations of individual time budget and facility opening hour (b-d)

RSTPs have an essential property:

$$\forall(x,t) \in RSTP(f,t_p,t_q,t_i,t_j,c,m), \forall t_x < t \land t_x \geq t_i : (x,t_x) \in RSTP(f,t_p,t_q,t_i,t_j,c,m)$$
(3)

Thus, for each space-time point of a RSTP, all coinciding space-time points at an earlier instant within the time budget belong to the RSTP as well. In other words, from each anchor location within a RSTP, an individual may always leave earlier within the time budget. Hence, the PPA of $RSTP(f,t_p,t_q,t_i,t_j,c,m)$ will be determined by all locations $x$ with $(x,t_i) \in RSTP(f,t_p,t_q,t_i,t_j,c,m)$.

RSTPs differ significantly from traditional STPs in being independent from individual anchor points. This is advantageous in several respects. First, it takes away the requirement of high-level individual activity/travel data. Second, this is also desirable from a computational point of view, since RSTPs have only to be calculated once in total, instead of once for each individual. Finally, yet most importantly, given a set of facilities with their opening hours and a presumed time budget, maximum travel time and minimum activity duration, RSTPs are representative for all anchor locations. Thus, area-covering maps may be produced to represent the PPAs of RSTPs, which will be *PrismMapper*'s core functionality. Whether a facility $f$ with opening hours $H_f$ is accessible to an individual at location $x$ with a time budget from $t_i$ to $t_j$ within a total travel time of at most $c$ for a duration of at least $m$ can be expressed by a function $A(x,t_i,t_j,f,c,m)$:

$$A(x,t_i,t_j,f,c,m) = \exists[t_p,t_q] \in H_f : (x,t_i) \in RSTP(f,t_p,t_q,t_i,t_j,c,m)$$
(4)

Given a set of facilities $F$ and the cut-off criteria $c$ and $m$, *PrismMapper* implements six accessibility measures (equations (5-10)) with respect to an individual at a location $x$ with a time budget from $t_i$ to $t_j$. Building on equation (4), these measures are defined as follows:

$$ACCESS(x,t_i,t_j,F,c,m) = \exists f \in F : A(x,t_i,t_j,f,c,m)$$
(5)

$$CUMF(x, t_i, t_j, F, c, m) = \left| \left\{ f \in F \middle| A(x, t_i, t_j, f, c, m) \right\} \right| \tag{6}$$

$$MINT(x, t_i, t_j, F, c, m) = \min_{f \in F | A(x, t_i, t_j, f, c, m)} \left( T(x, f) + T(f, x) \right) \tag{7}$$

$$MINTF(x, t_i, t_j, F, c, m) = \tag{8}$$
$$\left\{ f \in F \middle| A(x, t_i, t_j, f, c, m) \wedge T(x, f) + T(f, x) = MINT(x, t_i, t_j, F, c, m) \right\}$$

$$MAXD(x, t_i, t_j, F, c, m) \tag{9}$$
$$= \max_{f \in F | A(x, t_i, t_j, f, c, m)} \left( \max_{[t_p, t_q] \in H_f | B(x, t_i, t_j, f, t_p, t_q, c, m)} \left( \min\left(t_q, t_j - T(f, x)\right) - \max\left(t_p, t_i + T(x, f)\right) \right) \right)$$

$$MAXDF(x, t_i, t_j, F, c, m) \tag{10}$$
$$= \left\{ f \in F \middle| \begin{array}{l} \exists [t_p, t_q] \in H_f : \min\left(t_q, t_j - T(f, x)\right) - \\ \max\left(t_p, t_i + T(x, f)\right) = MAXD(x, t_i, t_j, F, c, m) \end{array} \right\}$$

In other words, for an individual with a time budget from $t_i$ to $t_j$ at location $x$:

- $ACCESS$ returns a boolean value which expresses whether (*true*) or not (*false*) there exists a facility in $F$ s(he) can visit respecting $c$ and $m$;

- $CUMF$ returns an integer value which represents the number of facilities s(he) can visit respecting $c$ and $m$;

- $MINT$ returns a ratio value which indicates the minimum total travel time that is required for visiting a facility $F$ from $x$, respecting $c$ and $m$, and returning to $x$;

- $MINTF$ returns the facility which corresponds to the minimum travel time specified by $MINT$;

- $MAXD$ returns a ratio value which indicates the maximum feasible duration for visiting a facility in $F$ respecting $c$ and $m$;

- $MAXDF$ returns the facility which corresponds to the maximum feasible duration specified by $MAXD$.

In addition, a parameter $n$ expressing the minimum number of accessible facilities is introduced. This parameter has been absent in the accessibility measures' formulas, but can be easily implemented by considering in equations (5-10) only these $x, t_i, t_j$ for which $ACCESS(x, t_i, t_j, F, c, m)$ is true for at least $n$ facilities.

Unlike the implicit assumption of an isotropic travel environment and a constant maximum travelling velocity underlying Fig. 2 and 3, *PrismMapper* implements all above accessibility measures within a much more realistic network-based travel environment with maximum travelling velocity varying all across the network (see section 3.2).

### 3.2. System

The *PrismMapper* system has three main components: (i) a GIS component, (ii) a computational module (CM) and (iii) a graphical user interface (GUI). *PrismMapper* is embedded in ESRI®'s ArcGIS™ Desktop GIS software as an ArcMap™ project template. ArcGIS™ Desktop is ESRI®'s most important desktop GIS product, offering a comprehensive set of tools to manipulate, analyse, visualise and store geospatial data in general and network-based data, including some place-based accessibility measures (see section 2), in particular. Embedding *PrismMapper* as a project template enables the integration of its functionality with the yet extended set of ArcGIS™ tools. The form of a project template ensures an easy distribution of the toolkit, as well as no installation requirements.

The core of the *PrismMapper* toolkit is the computational module (CM). It consists of several code modules written in Visual Basic using the ArcObjects object model (Burke 2003). CM is responsible for the calculation and mapping of the accessibility measures presented in section 3.1. To this end, CM relies on the following input data:

- Network dataset $ND$;

- Travel time attribute $T$;

- Set of facilities $F$;

- Time budget $[t_i, t_j]$;

- Maximum travel time $c$;

- Minimum activity duration $m$;

- Minimum number of accessible facilities $n$;

- Accessibility measure $AM$.

The network dataset $ND$ represents a transportation network which delineates the considered travel environment and thus the area of potential anchor locations. Networks are specified as ArcGIS™ Network Datasets that may be created from all kinds of data sources that participate in a transportation network such as road segments, junctions and turns. *PrismMapper* requires this network to have at least one travel time attribute $T$ (i.e. an impedance attribute expressed in temporal units) to enable the calculation of travel times. Optionally, some additional network analysis settings can be configured, including a distance threshold for matching facility locations to the network, and restrictions to account for when calculating shortest paths (e.g. one-way traversable network segments).

A facility dataset $F$ consists at least of the location and the opening hours for a set of service facilities. Facility locations are either obtained from a point data source, or by manually picking them on screen. They should be covered by the study area delimited by the $ND$. The facility locations are matched to the nearest network location on the $ND$ on the basis of a spatial search threshold which is configurable by the user. The opening hours are represented by their weekly schedules, i.e. a set of non-overlapping time intervals, given that this is the most common manner to express the opening hours of service facilities. Opening hours can be specified manually, or they can be loaded from a text file.

The individual parameters time budget $[t_i, t_j]$, maximum travel time $c$, minimum activity duration $m$, minimum number of accessible facilities $n$, and the accessibility measure $AM$ are all obtained from manual user input.

The computation of $AM$ proceeds as follows. First, the set $F$ is filtered to $F'$ which includes only those facilities of which the opening hours have a temporal overlap with the time budget $[t_i, t_j]$ (step 1). Second, for each facility $f$ in $F'$, the module calculates all shortest paths within the threshold time $t_j - t_i$ according to the attribute $T$. This is done once for all paths towards $f$ (step 2) and once for all paths from $f$ (step 3) in order to obtain all necessary travel costs $T(x, f)$ and $T(f, x)$ required in equation (2). Next, the intersection of all shortest paths towards and away from the same facility is made for each facility (step 4). For each network location which is on at least $n$ of such shortest path pairs, the module proceeds with assessing $AM$ using the respective formula of the equations (5-10) (step 5). The final accessibility results are spatially summarised to the level of network segments and stored as a polyline shapefile.

After the computation of the accessibility results, these are mapped within the ArcGIS™ map environment. Map type and symbolisation are chosen according to the data type of $AM$ (see section 3.1):

- The network locations for which $ACCESS$ is true are represented through a single-value map by means of a simple solid bright green line symbol;
- $CUMF$, $MINT$, and $MAXD$ are mapped onto a chloropleth map with in between five and seven equal interval classes. These classes are symbolised through solid line symbols with colours ranging from bright green for the network locations in the most accessible class to bright red for the locations in the least accessible class;
- $MINTF$ and $MAXDF$ are expressed by a chorochromatic map using a random color ramp to associate each facility with a unique color.

A useful toolkit should be reasonably efficient in terms of computation time and resources. The bottleneck operation in *PrismMapper* is the calculation of the accessibility measures described above (steps 1-5). Theoretical time complexity limits have not been listed here, since each computation step calls on a number of ArcGIS™ subroutines for which the precise algorithms are not available. The overall computational efficiency will highly depend on the size of the preset time budget, the maximum travel time and minimum activity duration, the size, number and spatial configuration of facilities with opening hours during the time budget, as well as on the scale, density and velocity characteristics of the transportation network at hand. Absolute computation times may fluctuate depending on the system platform and the exact version of ArcGIS™.

As a reference, we have reported the absolute run times of a scalability experiment which considered varying configurations in terms of maximum travel time, minimum activity duration and number of opened facilities during the time budget. To this end, a Tele Atlas MultiNet® road network database for the province of East Flanders (Belgium) including 16 473 points of interest (POIs) was employed. Seven different series of computation scenarios were set up by taking a random selection of 10, 20, 50, 100, 200, 500, and 1000 POIs – such that the larger selection contains the smaller selections – as facilities opened from 9:00 A.M. to 17:00 P.M. For each of the series, all accessibility measures have been calculated (steps 1-5) according to seven scenarios through an invariable time budget $[t_i, t_j]$ of 120 minutes from 12:00 P.M. to 14:00 P.M. and an increasing maximum travel time $c$ of 5, 10, 20, 30, 60, 90, and 120 min (and a proportionally decreasing minimum activity duration $m$ such that $c + m = 120$ min). All 49 (7 x 7) scenarios were processed on a 2.4 GHz Intel® Core™ i5 450M CPU running Windows 7 and ArcGIS™ 9.3.1. The resulting run times are plot in Fig. 4. As could be expected, computation time increases with an increasing number of opened facilities and an increasing maximum travel time (decreasing minimum activity

duration). The increase due to maximum travel time seems to level off somewhat from $c = 60$ onwards. This effect may be explained by the growing number of shortest paths that meet the limits of the study area for higher travel times (e.g. a maximum travel time of 120 min covers the large majority of possible trips within the network of East Flanders). Considering the high density and complexity of the road network in East-Flanders (66771 junctions and 85025 segments for 13 673 km of roads over an area of 2 982 km²), we conclude on the basis of observed computation times that the toolkit is sufficiently adequate for the purpose of large-scale accessibility analyses.

Fig. 4 – Computation time according to different scenarios

According to the underlying objective, the *PrismMapper*'s GUI is kept particularly simple. The toolkit's main application window and the associated workflow are depicted in Fig. 5 and 6.

Fig. 5 – *PrismMapper* workflow

Fig. 6 – *PrismMapper* main application window

## 4. Case study

In this section, we will elaborate a case study to illustrate the application of the *PrismMapper* toolkit. The study will examine the variation in accessibility to the public libraries in Ghent (Belgium) according to alternative scenarios of space-time constraints on the part of the individual as well as the libraries. A transportation network for Ghent has been compiled from Tele Atlas MultiNet® road network data. Car travel times can be estimated from this network using the shortest travel time attribute. The locations, presented in Fig. 7, and weekly opening hours of Ghent's municipal libraries have been obtained from the official city website

(http://www.gent.be). Ghent has one central main library and fifteen smaller branch libraries dispersed across the city.

Fig. 7 – Public libraries in Ghent (Belgium)

## *4.1. Reference scenario*

In order to configure the individual settings, we will consider persons who would like to make an evening library visit of at least half an hour[1] during a one-hour time budget on Monday from 6:00 P.M. to 7:00 P.M., and who do not want to travel by car for more than 20 minutes in total. This configuration is also depicted in Fig. 6. The accessibility maps for CUMF, MINT and MAXD for this reference scenario are shown in Fig. 8-10. In general, they reflect a high library accessibility. At least one library can be visited from practically everywhere in Ghent, with up to fourteen libraries downtown (Fig. 8).

The MINT map in Fig. 9, indicates that the minimum total travel time required to visit the nearest accessible facility is fairly limited (below 10 minutes on most locations), given the number of opened facilities and their spatial dispersion across the city. Note that MINT maps reflect physical proximity in a nuanced manner as they neatly articulate the discordance between network-based proximity, captured by back-and-forth shortest paths, and beeline proximity read from the map. Especially the directional nature of network segments may cause higher travel times than expected. Many locations in the vicinity of the main library, for instance, have rather high travel times due to the predominance of one-way streets in that part of city.

The MAXD map in Fig. 10 shows that the maximum feasible visiting duration ranges from 40 min to 60 min. This is a corollary of the preset maximum total travel time of 20 min

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[1] According to a 2004 study about public library services in Ghent (Vercruyssen 2005), a half an hour visit time should satisfy about 75% of the library visitors in Ghent.

on the one hand, and a maximal visiting time from 6:00 P.M. (start of the time budget) to 7:00 P.M. (the closing time of the libraries on Monday). Within the larger part of Ghent, a library can be visited for over 50 minutes, i.e. more than 83% of the time budget.

In the remainder of this section, we will compare the accessibility results for the reference scenario to those obtained for other scenarios by varying the time budget, transport mode, travel costs and facility opening hours respectively. Summary statistics for the numerical measures CUMF, MINT and MAXD have been listed for each scenario in Table 1.

Fig. 8 – Map of CUMF for the reference scenario

Fig. 9 – Map of MINT for the reference scenario

Fig. 10 – Map of MAXD for the reference scenario

| Scenario | CUMF | | | MINT (min) | | | MAXD (min) | | |
|---|---|---|---|---|---|---|---|---|---|
| | min | mean | max | min | mean | max | min | mean | max |
| 4.1 | 0.0 | 5.2 | 14.0 | 0.0 | 7.9 | 20.0 | 0.0 | 44.0 | 60.0 |
| 4.2 | 0.0 | 2.4 | 10.0 | 0.0 | 5.1 | 15.0 | 0.0 | 24.8 | 45.0 |
| 4.3 | 0.0 | 1.0 | 3.0 | 0.0 | 7.6 | 20.0 | 0.0 | 28.8 | 20.0 |
| 4.4 | 0.0 | 1.0 | 5.0 | 0.0 | 5.0 | 20.0 | 0.0 | 25.2 | 59.9 |
| 4.5 | 0.0 | 4.2 | 13.0 | 0.0 | 7.4 | 20.0 | 0.0 | 40.3 | 60.0 |

Table 1 – Minimum, mean, and maximum of CUMF, MINT, and MAXD for each scenario
(mean values have been weighted by network segment length)

### *4.2. Time budget*

Individuals differ much in terms of the time budgets they dispose of for conducting discretionary activities (Schwanen *et al.* 2008). *PrismMapper* allows for investigating how different time budgets affect accessibility. This is demonstrated in two alternative cases.

The first case involves a time squeeze scenario where the start of the time budget is postponed with a quarter of an hour from 6:00 P.M. to 6:15 P.M. (the end of the time budget being preserved at 7:00 P.M.) The resulting CUMF map is shown in Fig. 11. The effect of the time squeeze on the number of accessible libraries is general and strong. A significant

decrease is observed, when compared to the reference CUMF map (Fig. 8), with some parts in the north of Ghent now being deprived from accessing a library. Yet, the reduced time budget allows individuals to visit at least one library from within the major part of Ghent.

In addition to the size of the time budget, timing effects may influence one's accessibility of services as well. To illustrate the implications of having the same amount of time available at another moment, Fig. 12 provides the CUMF map in case the reference time budget is shifted from Monday to Tuesday. On Tuesday evening at most three libraries can be visited, even in the city centre, and a considerable part of the more peripheral areas have no library access at all. This is a sheer consequence of the fact that only the main library, and branches 2 and 4 are opened on Tuesday evening. Nevertheless, these three libraries still manage to serve Ghent reasonably well in this scenario, due to their relative dispersion across the city.

Fig. 11 – Map of CUMF for the case of a squeezed time budget

Fig. 12 – Map of CUMF for the case of a time budget on Tuesday evening

*4.3. Transport mode*

So far, we have considered library accessibility by car. To examine the influence of different transport modes, we have recalculated the reference scenario for the case of bicycle accessibility. Bicycles are a popular means of transport in Ghent and cycling is considered the most efficient way to travel across the city centre, especially within certain groups of the population such as students[2] and young adults. It is noted that public transportation cannot be dealt with by the current version of the toolkit. This would require implementing additional network algorithms for coping with the schedules and frequencies of various transport modes.

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[2] Ghent is the largest university town in Belgium, with about 65.000 students in 2010 (Braeckman 2010).

Since the MultiNet® network data does not contain a dedicated bicycle travel time attribute, we have estimated cycling travel times using a compromise solution. The approach consists of excluding highways and other exclusive motorways from the road network and allowing travel directions for non-motorised travellers[3]. The travel times have been estimated as the division of the shortest path distance and an average cycling speed of 15 km/h (El-Geneidy *et al.* 2007).

The resulting map for MINT is presented in Fig. 13. Libraries can be accessed on Monday evening by bicycle from within the larger part of Ghent. As could be expected, the car offers a better accessibility of the libraries and generally smaller travel times (Fig. 10), although this difference is less obvious in the inner city.

Fig. 13 – Map of MINT for the case of travel by bicycle

## 4.4. Opening hours

The above scenarios vary in terms of the constraints they impose on the part of the individual (time budget, transport mode), i.e. the demand side. Other opportunities lie in applying different configurations on the supply side, i.e. the service facilities. *PrismMapper* supports the analysis of variations of both the location and the operating hours of service facilities. Such comparative analyses may assist policy makers in facility planning and management, such as finding a suitable location for a new facility or rescheduling the regime of opening hours across facilities.

As an example, we have taken a potential facility closing scenario, e.g. due to budget cuts. Given that branch library 13 has the smallest collection size and the second smallest number of borrowers in 2010 (http://www.gent.be), we have considered the case of closing

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[3] One-way streets for motorised vehicles passable in both directions for bicyclists are common in Ghent.

this library on Monday evening. The resulting accessibility map for MAXD is shown in Fig. 14. It observed that the effect on feasible visiting duration of closing branch 13 on Monday evening is minimal: the duration is merely reduced within the small neighbourhood that directly surrounds the library, whereas the rest of Ghent remains unaffected. In addition, a fairly acceptable visiting duration remains feasible within the affected area, because the closed library is located in the well-served central area and close to the yet opened main library and library 3.

Fig. 14 – Map of MAXD in case library 13 is closed

## 5. Conclusion

This paper has introduced a novel GIS toolkit, named *PrismMapper*, for measuring and mapping the accessibility of individuals to services. The toolkit aims to combine benefits of both place-based and person-based accessibility measures basing on the time geographical concept of a space-time prism. Through the consideration of reverse space-time prisms, potential path areas can be derived that are representative for individual anchor locations in general rather than for one individual in particular. Thus, a foundation for deriving place-based measures has been obtained on the basis of person-based constraints including individual time budget, maximum travel time, and minimum activity duration. *PrismMapper* is also innovative in explicitly accounting for the opening hours of services in its assessment of accessibility. Accounting for the temporal component of service delivery is critical in order to assist the temporal planning of service facilities and the evaluation of temporal policies. Explicit attention to time constraints in accessibility measurement is also important in light of recognition of time and coordination problems in contemporary Western societies (see e.g. Moccia 2000, Deffner 2005, Southerton and Tomlinson 2005, Anxo and Boulin 2006, Boulin 2006, Szollos 2009). It also aligns with the emerging interest in time poverty issues in the

social exclusion literature (Kenyon *et al.* 2003, Lyons 2003, Cass *et al.* 2005, Neutens *et al.* 2010c, Farber *et al.* 2011).

The analysis capabilities of *PrismMapper* have been illustrated in a case study of accessibility to public libraries in Ghent (Belgium). The study has demonstrated how *PrismMapper* can be applied to generate accessibility maps according to alternative scenarios of constraints considered both on the part of the individual (time budget, activity duration, mobility resources) and on the part of the facilities (facility locations and opening hours). Investigation of the effects of such constraints on the accessibility of services can be useful for, among others, planners and decision makers who are faced with the planning and optimisation of services. The toolkit may, for example, be used to assess the suitability of a new facility location or to evaluate opening hour policies (e.g. Neutens *et al.* 2010c, Delafontaine *et al.* 2011, Neutens *et al.* 2011, Neutens *et al.* 2012). Other opportunities lie within transport studies. In section 4, the difference between car and bicycle accessibility has been studied. Alternative possibilities include analysing the impact of congestion (e.g. by associating different travel cost attributes to different time budgets) (Bilbao-Ubillos 2008, Noland 2008) or modifications to the transport infrastructure (Meyer and Miller 2001, Vandenbulcke *et al.* 2009).

Admittedly, the *PrismMapper* does not arrive at integrating all of the benefits of true person-based approaches. Nevertheless, a further step to support an even more fine-grained integration of person-based constraints may be to consider individual time profiles. Specific groups of a population (e.g. fulltime employees, students, pensioners, etc.) may dispose of similar budgets of available time for accessing opportunities. Therefore, accounting for specific (weekly) time profiles, instead of a single time budget, may be a promising extension of the toolkit. We aim to address this opportunity in future work.

Apart from the yet mentioned contributions, *PrismMapper* has been developed with the eye on two additional objectives which have hitherto often been ignored in existing related tools (see section 2). The first of these has been that the results generated by the toolkit should be useful and in as much as possible comprehensible for end-users who are not acquainted with the accessibility literature. We believe to have demonstrated this through the case study presented in section 4, although a genuine user study may support a further evaluation of this objective.

The other objective has been that the toolkit should be simple and user-friendly. This has been achieved through an undemanding user interface and an easy workflow which consists, in essence, of three steps: launching the application, configuring the input data and parameters, and processing the results. Apart from user-controllable parameters, the toolkit relies on readily available data about the service facilities and the transportation network at hand. Data about the locations and opening hours of service facilities are generally publicly available. Yet, given that these may not be available in a standardized digital format, *PrismMapper* offers the flexibility to manually configure them. Transportation network data, on the other hand, is abundantly available for many parts of the world. Some network data sets can be freely downloaded in appropriate formats, such as from the websites of the U.S. Census Bureau (http://www.census.gov/geo/www/tiger) and OpenStreetMap (http://www.openstreetmap.org). Furthermore, the embedding of the toolkit within an ArcGIS™ project template allows an easy distribution and takes away any installation requirements.

The incorporation in a larger GIS has another advantage. *PrismMapper* reports all accessibility results at the level of network segments. This is a fine-grained and transparent representation in the sense that accessibility is only calculated on the basis of travelling along the network. Many applications will however desire accessibility measures to be reported on

an aggregated level according to a certain administrative or statistical zoning. Given that ArcGIS™ implements many different overlay operations to obtain such aggregations, the most fine-grained resolution has been chosen intentionally for *PrismMapper*, leaving a posteriori aggregation possibilities to the user.

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